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Positive feedback, lock-in, and environmental policy

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Abstract. During the last several decades, modern economic methods have been brought to bear on problems of environmental policy, with powerful and influential results. However, this policy-making paradigm often relies on some of the most restrictive sets of assumptions of microeconomics: the convexity conditions required for competitive markets to be Pareto-efficient. When *positive feedback* or *lock-in* occurs, these assumptions do not hold, and standard economic analysis of environmental policy may lead to technologically inferior outcomes, e.g., pollution control costs that are higher than necessary. This paper considers positive feedback in several different forms, and argues that it commonly occurs in markets that affect environmental policies, such as markets for energy technologies. The discussion examines how the standard paradigm for environmental economics breaks down in the presence of positive feedback or lock-in, and considers some policy responses to this problem. The case of SO_2 trading helps illustrate how the standard paradigm can miss important technological opportunities for lower-cost pollution mitigation. The argument also suggests how the standard paradigm encourages end-of-pipe solutions and tends to overlook options like pollution prevention strategies, which can sometimes provide more economical environmental improvements.

Introduction

During the last several decades, a new paradigm has emerged for design and evaluation of policies that mitigate the environmental impacts of economic activity. This paradigm has drawn on a well-articulated mathematical description of market economies, developed by economists since about 1950 (e.g., Koopmans, 1957). This paper examines how this foundation has been both a blessing and a curse. The assumptions of this paradigm – often implicit in environmental policy making – will cause it to overlook important opportunities for cost-effective environmental improvement. The concepts of *positive feedback* and *lock-in*, discussed below, provide an organizing framework for uncovering and exploiting these hidden opportunities.

The current environmental policy paradigm

Current practice in environmental policy making emerged largely from one key insight: acknowledging the importance of environmental impacts that are not priced in competitive markets, i.e., environmental externalities (Baumol and Oates, 1971; Roberts and Spence, 1976; Starrett and Zeckhauser, 1974). Many earlier economic policy analyses ignored externalities even though their existence violates the underlying assumptions that guarantee the efficiency of competitive market outcomes. In recent years, environmental impacts have gained increasing attention. This increased attention may be partly because the problems have gotten more severe, and partly because attitudes toward the environment have changed. In addition, the availability of more powerful analytic and computational tools allowed these effects to be included in economic analysis.

In many cases, environmental externalities can be incorporated into economies by straightforward systems of effluent taxes.[2] Economic arguments also show that there is an equivalent cap-and-trade scheme that will generate the same outcome as a given system of pollution taxes (Starrett and Zeckhauser, 1974). Cap-and-trade policies, such as the one used for controlling SO_x emissions in the utility industry, are often considered preferable for political reasons.[3]

In theory, tax policies and cap-and-trade policies can be considered equivalent, but in practice there are important differences. Because the relevant supply and demand functions are known only imperfectly, the results of these policies are uncertain. Under a tax scheme, the marginal cost of abatement will be known, but the amount of abatement that will result will be unknown *a priori*. Conversely, under a cap-and-trade system, the amount of abatement will be known, but the costs will only be known *ex post*. There are also significant issues – and a large body of literature – associated with measuring the cost of environmental impacts, in order to set appropriate effluent tax or quota levels. Both of these problems, while often important, are ignored for the purposes of this discussion.

Under appropriate assumptions, tax or cap policies restore an efficient economic equilibrium in a competitive market economy (see e.g., Koopmans, 1957). This fact, and the assumptions that go with it, are the source of both the blessing and the curse conferred by contemporary microeconomics on environmental policy making. The blessing is the efficiency of the equilibrium. One corollary of this efficiency is that the environmental goal cannot be achieved at a lower cost. The curse is that the assumptions required to guarantee this efficiency rarely hold in practice, while the elegance of the efficiency result provides a strong temptation to ignore this critical fact. This oversight can lead to sub-optimal policies, in particular technology choices that are not in fact minimum-cost approaches to pollution mitigation. To illustrate this observation, consider the following example, taken from the United States' experience with SO_2 trading.

SO_2 trading

The SO_2 trading system created by the United States' 1990 Amendments to the Clean Air Act is widely considered to be a successful environmental policy, and has generated interest in cap-and-trade schemes for dealing with other environmental issues. The SO_2 trading program led to a significantly lower compliance cost than could have been achieved under command-and-control regulatory policies (Burtraw, 1996). In fact, the cost of compliance was substantially less than the expectations of many analysts based on models of the trading system before its outset. *A priori* estimates of the market price of SO_2 allowances were at least twice the actual market outcome, and often much higher.[4]

This discrepancy suggests that the modelers did not understand the techology of sulfur reductions well enough to predict the price in advance. This is not an indictment of their economic acumen, however. In hindsight, the overestimate of allowance prices should come as no surprise. Even the operators of the plants involved in the SO_2 allowance markets might have been hard pressed to specify exactly which technologies and practices would be used to reduce emissions. The economic incentive to devise these practices began only with the advent of SO_2 trading.

Monetary incentives can only approximate all the economic dimensions of environmental impact. Moreover, economic agents may respond only imprecisely to monetary incentives (Simon, 1959). These observations help explain why it is difficult for policy to induce all the potential innovation that could improve environmental-economic performance (Norberg-Bohm, 1999). The following discussion suggests why there may be technologies available that could lower compliance costs even further than observed so far – but which have not been adopted under SO_2 trading because higher cost technologies are 'locked in.'

Positive feedback and lock-in

Positive feedback in markets

The concept of positive feedback has become relatively familiar to the policy community, but it has a particular connotation in economics that is less well understood. A familiar market history provides a definition by example. (For an extended introduction to positive feedback in the economy, see Arthur, 1990.)

When VCRs appeared on the market, Betamax and VHS format machines competed on a relatively equal footing. Gradually, however, VHS gained a slight edge in market share.[5] This small lead tended to become self-reinforcing through the following chain of events: Consumers considering purchasing a VCR noticed slightly more VHS-format tapes in video stores – because there was slightly more demand for them. This observation increased the probability that consumers would purchase VHS machines, increasing their share of the installed product base, further increasing the fraction of VHS tapes on the shelves and increasing VHS' market share even further. The self-reinforcing nature of VHS' advantage in market share illustrates the economic meaning of 'positive feedback,' as illustrated in Figure 1.

The obvious end result of this process was that VHS acquired an overwhelming market share, and the Betamax format became virtually extinct, a result that tended to be self-perpetuating. The stock of VHS-format tapes on retail shelves and in consumers' home libraries dramatically increased the

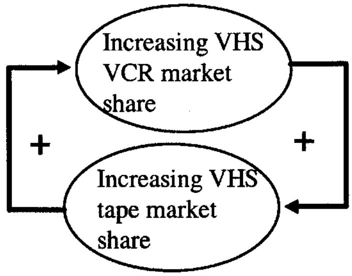

Fig. 1. Positive feedback in the VCR market.

perceived cost of switching to another tape format. This kind of self-perpetuating market dominance is called *lock-in*.

The prevalence of positive feedback

Positive feedback and lock-in are common – but often ignored – phenomena in the industrial and postindustrial marketplace. Consider the following examples: standardization on a single gauge for railway equipment throughout most of the world; the dominance of automobiles, specifically internal-combustion-powered automobiles; the dominance of light-water reactors in nuclear electric generating stations; the virtual monopoly enjoyed by the standard 'QWERTY' keyboard layout; and the tendency for critical inter-operating software markets such as operating systems to be dominated by a very small number of competitors, often just one.

One mechanism that can create positive feedback is the learning curve that applies to production. More production experience reduces price, which increases market share, which further increases production experience and relative advantage in price. Virtually all manufactured products are subject to learning curves, and so all markets for emerging technologies are potentially subject to positive feedback. The market significance of this positive feedback depends on how much the learning curve influences the relative prices in the market. This observation helps explain why positive feedback and lock-in are commonplace in modern markets. However, there are also several other mechanisms that can drive the positive feedback process, such as the one in the VCR example (Cowan and Kline, 1996).

Dynamics and implications of positive feedback

Much of neoclassical economics implicitly or explicitly assumes decreasing returns to scale in production, and enough other 'regularity' conditions to ensure that a unique equilibrium will exist. Most standard environmental policy

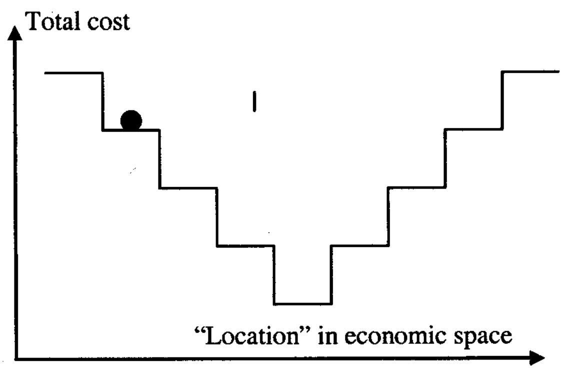

Fig. 2. The neoclassical view of equilibrium.

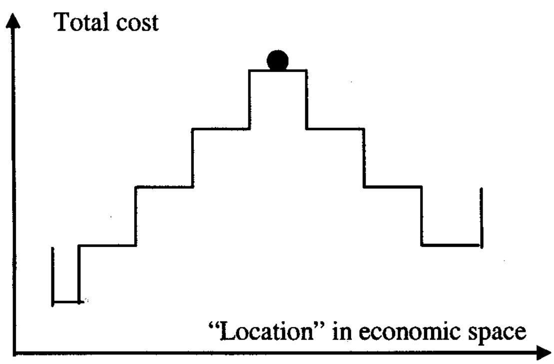

Fig. 3. Path dependent case.

approaches rely implicitly on this kind of characterization. Where positive feedback is present, however, these assumptions cannot be maintained. There may be multiple equilibria – or no equilibria. The departure from a unique-equilibrium world presents both difficulties and opportunities for policy makers; it changes all the rules of the game.

Figures 2 and 3 provide an analogy that illustrates the difference between a 'neoclassical' view, which assumes a single equilibrium, and a view in which there are two equilibria and positive feedback. In these figures, 'location in economic space' might correspond to the amount of labor input used in producing the required amount of goods.[6]

Figure 2 represents the single-equilibrium case. Imagine the black ball to be bouncing around on the stairs of the figure, driven by some random exogenous shocks. Eventually, the ball will wind up near the bottom, as competitive firms minimize their costs. If the stocks are small enough, the ball will eventually stay at the very bottom step (equilibrium).

Figure 3 represents the path-dependent case. It is not by coincidence that this diagram looks much like Figure 2 turned upside down. Here, the ball

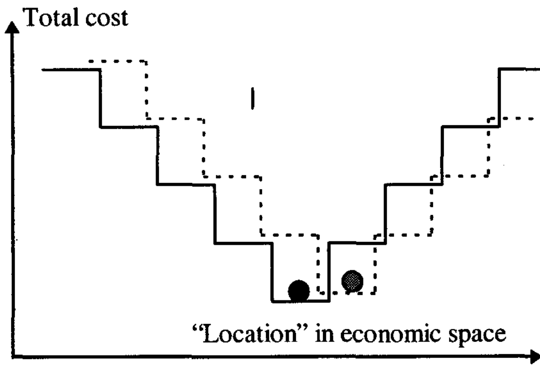

Fig. 4. Policy impact – single equilibrium case.

bounces around on the landscape, starting at the center as indicated. In this case, the ball will wind up in the bottom of one well or the other.

Several features of this case distinguish it immediately from the one illustrated in Figure 2:

- We cannot tell *a priori* where the ball will wind up.
- Costs are different in the two outcomes.
- At the beginning of the process, the ball may jump back and forth between the two sides.
- Once the ball has gone far enough down one side or the other, it is unlikely to switch sides again.
- If we started the ball in a slightly different place, the expected outcome could be quite different.[7]

Policy implications

Policy looks quite different in the two situations represented by Figures 2 and 3. Suppose that in the world represented by Figure 2, policy makers desire to move the equilibrium in one direction or the other. This change can be accomplished by a number of different policies, which move the landscape around, as illustrated in Figure 4.

There are two things to notice about this neoclassical view of policy:

- The response to the policy is 'smooth,' i.e., a small tax moves the equilibrium a little, a slightly larger tax moves it a little more, and so on.
- The end result will be the same no matter when in the process the policy is applied.
- If the policy is removed, the equilibrium returns to its original location.

Thinking about applying the same kinds of policies in the two-equilibrium case of Figure 3 illustrates a number of key points about the difference between the neoclassical and path-dependent viewpoints. None of the three observations about policy in a neoclassical framework hold in this case. The response to policy will not be smooth – it will contain discontinuities. In addition, *when* the policy is applied makes a significant difference. If the ball starts out in the center, it can be manipulated to one side or the other fairly readily at the beginning of the process. But if the ball has settled down into one of the wells, it will take a much more aggressive policy to move it over the top into the other basin. Another policy choice at this point would be to operate the same way as in the neoclassical case, applying a modest policy to move the equilibrium slightly, as illustrated in Figure 4. The choice between the two approaches depends on relative costs and benefits.

This discussion helps reinforce the two following conclusions:

- A less desirable technology can dominate in market competitions.
- There can be multiple market equilibria. And when one equilibrium is reached, it can be very difficult even to detect the possibility of moving to another, qualitatively different equilibrium.

These two possibilities have strong implications for environmental policy, as discussed next.

Environmental policies under positive feedback

Difficulties with the standard paradigm

Many existing technologies are currently locked in, including many with significant environmental implications. Fossil-fuel electric generating plants are just one example. These technologies are locked in both because of their long production history, which has reduced their costs many fold, and because they are supported by an extensive infrastructure of fuel supply, maintenance, and other ancillary services. Because of positive feedback, environmental policy based on the standard economic assumptions will often overlook cost-effective opportunities to reduce the cost of achieving environmental quality.

Consider a cap-and-trade system for controlling a given pollutant, for example. Once the system is in place, we see producers installing pollution control devices, more efficient fuel using equipment, and similar measures. Prices rise in response to these increased control costs, and consumption decreases slightly to clear the market. This outcome may look optimal: all marginal control costs are the same. For the given level of pollution implied by the cap, it is difficult to see how the policy could be improved.

Where there is positive feedback, however, we may be able to do much better than this. What the conventional policy does is shift the *ex ante* equilibrium slightly, around the edges, as described above. But the existence of positive feedback implies that there may be a qualitatively different equilibrium. And the second equilibrium may be distinctly preferable to the two other situations. One may ask why such a preferable outcome did not arise in the first place. The answer, as noted previously, is that inferior technologies can prevail in market competitions involving positive feedback.

For example, Cowan (1990) describes the penetration of light-water reactors into the electric power market. In this case, the U.S. government sponsored research and development that led to the development of light-water reactors for powering nuclear submarines. So far, this policy follows the neoclassical view of the government providing R&D funding for national defense, which is a public good. Light-water reactors were arguably the right choice for the submarine application, given all the technical and strategic considerations.

After they were chosen for use in submarines, light-water reactor designs dominated the nuclear market for utility power generation by virtue of the experience of manufacturers in producing them for the Navy. This outcome represented the technology path of least resistance. Many have argued that other nuclear designs are better suited to the utility power market, but light-water reactors are now locked in (Cowan, 1990).

Shifts in environmental policy

Another reason that environmentally inferior technologies may dominate is that a technology that was preferable when pollution damages were (implicitly) valued at $0 may not be preferable when their environmental consequences are reassessed. We might now evaluate the damages at, say, $50 per unit of emissions. But the technology that developed under the $0 per unit pollution prices may now be locked in, and it might not be dislodged by imposing a $50 per unit effluent charge or its equivalent cap-and-trade system. In this case, the $50 effluent fee may move the economy to an equilibrium that looks optimal, but masks dramatically preferable alternatives.

A shift in policy, such as the example just above, can provide an opportunity for positive feedback processes to emerge. Dramatic changes in relative prices can create markets for new products, which often have steep learning curves – that is, the initial cost is quite high but this cost decreases rapidly with production experience. These steep learning curves can create significant positive feedback effects. Thus, besides the fact that the existing technology may be locked in, the best emerging technology from the set of new possibilities may not prevail in a market competition.

Policy changes that create this kind of situation can arise from a reevaluation of the economic cost of pollution, as suggested above. The most cost-effective response to such a policy shift can often be a qualitative shift in technology: a change from conventional coal boilers to atmospheric fluidized-bed combustion, to nuclear generation, or to renewable energy, for example. The discussion of lock-in should help explain the fact that we often do not see these quantum leaps in technology, even when they would be beneficial from a societal viewpoint. We more often see marginal changes that preserve the essence of the status quo. Preferences for the status quo are also strengthened by risk-averse behavior exhibited by firms, particularly in regulated industries.

End-of-pipe solutions

The discussion above sheds some light on environmental strategies focused primarily on pollution abatement at the 'end of the pipe.' These technologies often result from marginal incentive policies prescribed by the standard paradigm. Within the framework of that paradigm, they may appear to be the least-cost solution. However, there are often better solutions than those that focus only on the end of the pipe. The next section explores how we might uncover some of these solutions through alternative policy approaches.

Policies to mitigate the impacts of positive feedback

As suggested above, positive feedback severely complicates the policy-making process. There are no simple policy fixes. However, there are a number of policy responses to positive feedback. These responses generally pursue one or both of the following objectives:

- *Coordinate* beneficial shifts in technology, where such a shift is impossible without such coordination.[8]
- Encourage *experimentation* with alternative technical and institutional approaches to environmental management, especially those that are qualitatively different from the outcome under conventional policies.

These two approaches are discussed in greater detail below.

Coordination

Technology lock-in can be driven by the benefits of widespread technology standards. The examples of standard railroad gauge and television broadcast encoding schemes come readily to mind. Public policy can play a useful role in coordinating the switch to different industry standards that provide improved performance, and to the development of good standards for newly emerging technologies where standardization will be important.

Cowan and Gunby (1996) provide a dramatic example of overcoming lock-in by coordinated action. In this case, the Agricultural Extension Service helped cotton growers in Texas coordinate a transition from conventional to integrated pest-management practices. Coordination was essential to success, because if a near neighbor continued using conventional pest control, integrated pest management would not have been effective.[9] The transition was essential because traditional pest control was failing due to pesticide-resistant insects. The intervention was straightforward and effective, and the Texas cotton sector recovered robustly. Growers in nearby Mexico did not make this transition, and were largely wiped out by uncontrollable pests.

Experimentation

The overall goal of encouraging increased experimentation applies to several different situations and types of policies. In the early phases of technology competitions, this goal implies that public-sector sponsorship or provision of R&D services can be beneficial. Analysts have known for some time that R&D will often be under-supplied in competitive markets (Nelson, 1959). More recent economic research suggests that where positive feedback effects are important, strategic public-sector R&D efforts can play an even more important role than previously suspected (Cowan, 1991). These efforts can mitigate a general tendency for one technology to become locked in too early in the development process, before it is clear that it is the best solution in the long run. Strategies that encourage continued experimentation can thus reduce the probability that an inferior technology will dominate the market. (An interesting corollary to this result shows that it is generally not advisable, and often not possible, to reduce this probability to zero.)

Public-sector research aimed at improving the cost and performance of photovoltaic cells, for example, supports research on a variety of different cell materials and designs simultaneously (U.S. Department of Energy, 2000). Collaborative semiconductor industry R&D also supports a number of parallel approaches to solving the key technology problems identified in the 'Roadmap' for semiconductor industry development compiled by Sematech (Semiconductor Industries Association, 1999). The arguments above suggest that public (and collaborative) research should apply these strategies more broadly, and for longer periods, in view of the possibilities for lock-in during the development process.

Experimentation also has a role to play in more mature markets, where one set of techniques may already be locked in. These situations present difficult challenges for policy makers. Overturning existing lock-in can be difficult and expensive, and may not be worth the cost. However, as mentioned before, an existing lock-in situation may be hiding techniques that are superior, but are kept out of the marketplace by this lock-in. There may not be a generally applicable algorithm for identifying such superior technologies, but several recent trends in environmental policy making suggest some possible approaches.

All these recent developments can be characterized as taking a 'systems' or broadened view in the search for policy options. It is not surprising that such efforts might be effective in improving a situation where a locally self-sustaining situation (lock-in) is not a global optimum. Pollution prevention strategies represent one increasingly popular approach that fits this description. Even without a precise definition of 'pollution prevention,' it is clear that these strategies encourage a broader view, by asking how emissions could be prevented in the first place rather than mitigated afterwards. This approach is one way of asking what potentially superior techniques might be available that are not part of the status quo solution.

The emerging concept of 'market transformation' also implicitly questions whether the existing equilibrium is the best possible alternative. Market transformations are by definition a shift to a qualitatively different market outcome, where a different set of technologies dominates. Strategies that recognize the value of market transformations and seek to engineer them implicitly recognize the arguments given above, i.e., that inferior technological solutions may have become locked in.

A third way of asking these questions involves the development of technology strategies, broadly construed. Surveying a broad range of technology options – *without* considering what the market outcomes might produce – represents another way to identify techniques that could improve on an existing, locked-in, outcome. The considerations of lock-in suggest that these surveys should be conducted from the widest possible perspective, applying a variety of tools for encouraging creative thinking. Roadmapping exercises are one of many possible processes for developing and assessing technology strategies.

Regulation

Regulatory authority provides a set of public policy tools that can be used to help mitigate existing or potential lock-in. Used judiciously, a variety of regulatory approaches can be effectively used as part of a strategy to encourage experimentation and develop efficient industry standards.

Existing regulatory authority deals relatively comprehensively with the administration of existing standards and the development of new ones, such as for high-definition television. The question of changing existing standards is less often addressed by the existing regulatory infrastructure, but it may be at least as important.

Flexibility in regulatory approaches can help minimize the chance that lock-in will prevail, by allowing for a number of alternative approaches to meeting a performance-based standard, for example. Burtraw (1996) illustrates how regulatory flexibility contributed strongly to reducing costs in the effort to reduce SO_2 emissions. Norberg-Bohm (1996) also emphasizes the importance of regulatory flexibility, and suggests that U.S. policy could be pushed further in the direction of providing for more flexible compliance strategies.

Concluding remarks

This paper illustrates how positive feedback and lock-in complicate the problems of environmental policy making. Solutions based on the standard paradigm will often fail to produce the best available approach. At first glance, dealing with these complications may seem daunting: there are no simple, generally applicable solutions. However, the discussion of positive feedback does suggest general directions for expanding on our existing arsenal of economic policy instruments:

1. *Broaden the view.* The potential failure of the standard economic policy paradigm to uncover lower-cost solutions can often be traced to a narrow view of the industry to be regulated, or of the life cycle of the product being manufactured. For example, including end-use electricity conservation technologies in the strategy to reduce utility SO_2 emissions could reduce the overall cost. Recent initiatives in the area of pollution prevention are moving in this direction.
2. *Lengthen the time horizon.* Lock-in sometimes represents a situation where focusing on the short-run can increase long-run costs.[10] Encouraging business decisions to focus on longer-term issues is difficult, but more could be done to explore different means of accomplishing this goal. Norberg-Bohm (1999) describes one approach to this issue in German environmental policy.
3. *Provide for flexibility in the response.* Providing for flexibility in the response to environmental policy can help mitigate lock-in. Flexibility has other benefits as well (Norberg-Bohm, 1999; Burtraw, 1996).

Recent trends in environmental policy investigation, such as pollution prevention and the quest for market transformations, hold promise in uncovering and exploiting improved environmental policies that are superior to those that emerge from the standard approaches.

Notes

1. The author would like to thank John Atcheson and Robin Cowan for many useful conversations, and an anonymous referee for many useful comments and suggestions.
2. For example, Lave and Seskin (1970) demonstrate that effluent taxes can be used to induce the least-cost solution to meeting a given environmental quality goal.
3. For example, when the author was supporting the development of the U.S. National Climate Change Action Plan, members of the interagency task force in charge of the project made it clear that new taxes were not to be included in the plan, although commitments to quotas could be considered. See also Norberg-Bohm (1999).
4. Burtraw (1996) observes that a major determinant of lower-than-expected allowance costs was innovation in the factor markets for the inputs to the affected plants. We will return to the issue of innovation later in the discussion.
5. Much has been written about this event, which appeared insignificant at the time but turned out to be a critical turning point. See, for example, Arthur (1990). However, the reason that VHS acquired this early lead is not important to this discussion.

6. Here the discussion refers to the producers' problem formulated in the form:'Choose a set of inputs and technologies to produce the required set of output goods at minimum cost.' Of course, there are many inputs to be chosen, and Figures 2 and 3 can be thought of as the projection of this multidimensional landscape onto the plane determined by the cost axis and the labor axis.
7. The analogy expressed in Figures 1 and 2 is obviously informal. The economic conclusions suggested by this analogy are developed rigorously in Cowan (1991).
8. A simple example of a shift in technology that is impossible without thorough coordination is switching from driving on the left-hand side of the road to driving on the right. Here, changing standards is only workable if everyone can switch at very close to the same time. An example in environmental control technologies is the case of integrated pest management, described in Cowan and Gunby (1996).
9. Integrated pest management relies significantly on 'friendly' insects to manage pests that damage crops. Pesticides used on a nearby tract can kill the insects that are essential to integrated pest management, leaving enough pest insects to cause significant damage.
10. Both the adoption of the light-water reactor for electricity production, described in Cowan (1990), and the lock-in of pesticide-based pest management described in Cowan and Gunby (1996) are examples where decisions based on short-run considerations led to higher costs in the long run.

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